Engineering precision surgery: Design and implementation of surgical guidance technologies

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OUTLOOK

CHAPTER 9

COMPUTER-ASSISTED SURGERY: VIRTUAL- AND AUGMENTED-REALITY DISPLAYS FOR NAVIGATION DURING UROLOGICAL INTERVENTIONS

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ABSTRACT

The purpose of this review is to provide an overview of the developments made for virtual- and augmented-reality navigation procedures in urological interventions/surgery. Recent findings show that navigation efforts have demonstrated potential in the field of urology by supporting guidance for various disorders. The navigation approaches differ between the individual indications, but seem interchangeable to a certain extent. An increasing number of pre- and intra-operative imaging modalities has been used to create detailed surgical roadmaps, namely: (cone-beam) computed tomography, MRI, ultrasound, and single-photon emission computed tomography. Registration of these surgical roadmaps with the real-life surgical view has occurred in different forms (e.g. electromagnetic, mechanical, vision, or near-infrared optical-based), whereby the combination of approaches was suggested to provide superior outcome. Soft-tissue deformations demand the use of confirmatory interventional (imaging) modalities. This has resulted in the introduction of new intraoperative modalities such as DROP-IN US, transurethral US, (DROP-IN) gamma probes and fluorescence cameras. These noninvasive modalities provide an alternative to invasive technologies that expose the patients to X-ray doses. Whereas some reports have indicated navigation setups provide equal or better results than conventional approaches, most trials have been performed in relatively small patient groups and clear follow-up data are missing. However, the reported computer-assisted surgery research concepts do provide a glimpse in to the future application of navigation technologies in the field of urology.

KEY POINTS

- At present, soft-tissue deformations demand the use of interventional imaging or tracing modalities that confirm the real-world surgical target location.
- Due to their dose exposure, intraoperative use of X-ray-based imaging devices is undesirable, and technologies that provide a noninvasive alternative (e.g. gamma probes, US, and fluorescence) are much in demand.
- Early clinical studies have demonstrated the potential of virtual reality and augmented reality models (2D and 3D) to improve the surgical (navigation) accuracy.
- To date, a plurality of surgical navigation approaches has become available, thereby covering a range of urological interventions.

INTRODUCTION

The impact of computer technologies on life in the western civilization is an undeniable fact. One of the many advancements that has been created is the availability of navigation systems. Using, for example, smartphones, we are now able to accurately determine our geographic location and navigate ourselves efficiently from point A to point B, while even dynamically responding to deviations from the plotted route (Figure 1). Such navigation is made possible using a combination of urban roadmaps and satellite-based tracking systems such as the global positioning system (GPS). We, and others, have reasoned that a similar navigation concept, when translated to surgical interventions, could greatly impact healthcare. Building on the advancements made in medical imaging technology, anatomy and/or disease-related images of individual patients can be created. Such images can, subsequently, be used to provide detailed and interactive surgical roadmaps [1]. This computer-assisted surgery (CAS) concept creates the potential to increase the accuracy of lesion identification, and with that improves the surgical accuracy, logistics, and decision-making (Figure 1) [2]. Herein, surgical roadmaps can be used in different forms: they can be presented separately in the operating room or next to the laparoscopic-feed to allow the operating urologist to study the targeted tissue in detail during the procedure; they can be presented via virtual reality displays that provide, for example,

Figure 1. Analogy comparing navigation in everyday life with navigation during surgery. *Similar to navigation approaches applied during everyday life* ***(a)****, a surgeon can use a combination of guidance technologies to guide himself or herself quickly and efficiently to the surgical target [e.g. tumor, (metastatic) lymph node or kidney stone]* ***(b)****. These technologies can follow each other in consecutive order: disease description ('Descriptive'), two-dimensional preoperative imaging ('2D map'), three-dimensional preoperative imaging ('3D map'), 'GPS-like' virtual reality navigation ('VR navigation'), 'GPS-like' augmented reality navigation displays ('AR navigation') and intraoperative imaging/tracing ('Confirmative imaging').*

distance-to-target estimations; they can be presented as augmented reality overlays onto the real-world environment using (laparoscopic) video-feeds (Figure 1).

While rough navigation on a general anatomic map was already attempted as early as 1889, 'modern patient-specific' navigation (that is navigation based on individual patient scans) has only been used since 1986 [2]. At present, the field of surgical navigation offers a plurality of navigation concepts and methods. Most of these have been applied in neurological and orthopedic surgery, where the rigidity of the surgical field supports the alignment between the surgical roadmap and the actual surgical field. Soft tissues are, however, subject to movement – a feature that inherently complicates the registration process [3]. Nevertheless, due to their high potential, soft-tissue related navigation efforts have been explored in a translational research setting, as discussed in a number of reviews relevant for the topic [1–7]. During the past years, navigation in the field of urology has rapidly expanded, including novel indications and first-in-human applications. To provide a structured report of these evolutionary progressions, we have classified them into navigation for disorders in the urinary system or reproductive organs.

URINARY SYSTEM

Navigation efforts for urinary disorders are mainly focused on nephrolithotomy (urolithiasis) and nephrectomy (renal cell carcinoma). For these applications, (cone-beam) computed tomography (CT) – the modality proposed for these indications in the European Association of Urology guidelines – is the main modality used for the creation of the roadmap that provides the basis for the navigation-process [8,9].

Navigation during percutaneous nephrolithotomy

Rassweiler et al. [10,11] has clinically applied navigation technologies during nephrolithotomy using a futuristic iPad tablet-assisted guidance approach (Figure 2a). Using CT-derived roadmaps, this approach provides a movable two-dimensional augmented reality 'window into the body,' thereby facilitating the optimal access site for needle puncture. Roadmap-to-patient registration was realized using a vision-based tracking setup, encompassing the two-dimensional camera of the iPad and radiopaque colored fiducial markers, placed on the patient's skin. During needle puncture, fluoroscopy allowed adjustments to be made from the plotted needle course. A comparison to traditional ultrasound-fluoroscopy combinations, yielded a similar outcome, but also revealed that significantly higher X-ray doses and longer puncture times occurred with the iPad approach [11]. Incorporation of electromagnetic needle tracking was proposed as a future refinement. In a porcine study, Rodrigues et al. demonstrated that the incorporation of an electromagnetic sensor at both the needle and catheter-tip allowed needle placement to be performed by relying on the electromagnetic tracking

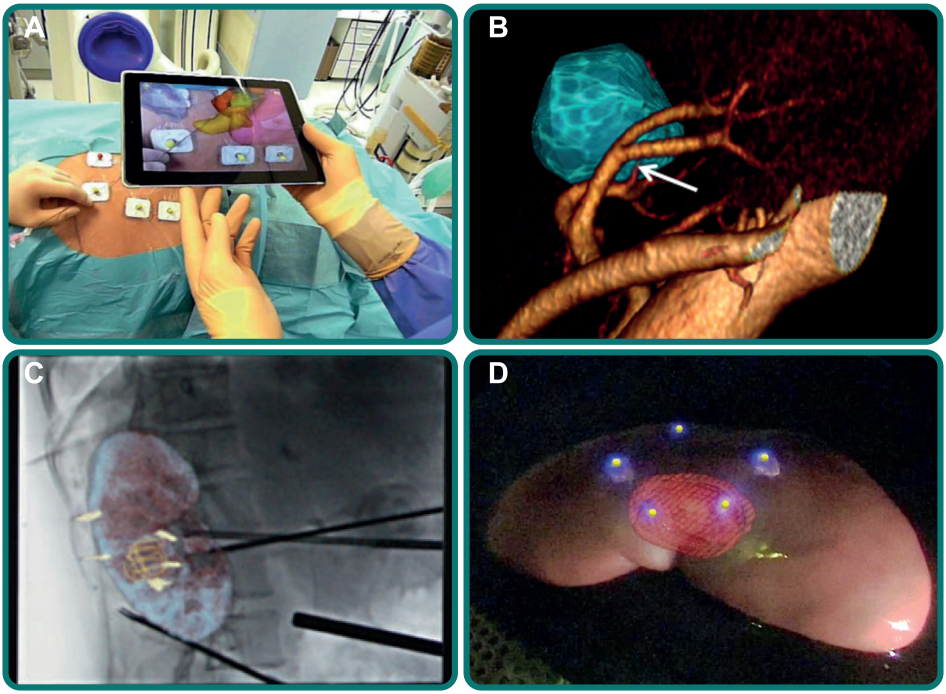

Figure 2. VR and AR technologies for navigation in the urinary system. (a) *iPad-assisted percutaneous access to the kidney during nephrolithotomy, providing CT-based AR 'window in to the body' [12].* ***(b)*** *CT-based VR model of renal cell carcinoma, to be used parallel to (RA)LPN, providing insight in the tumor-surrounding vasculature [13].* ***(c)*** *AR overlay of kidney and tumor models (including intra-abdominal fiducials) in the real-time fluoroscopy images for (RA)LPN [14].* ***(d)*** *AR overlay of tumor model in the real-time laparoscopic-feed using metabolizable and fluorescent fiducials [15].*

and vision of the ureteral fiberscope only [16]. After placement of the catheter tip next to the kidney or ureter stone via ureterorenoscopy, electromagnetic tracking supported real-time monitoring of the needle tip and stone relative to each other, abandoning the need for fluoroscopy. Integration of electromagnetic needle tracking and the iPad approach could thus help limit the X-ray dose while allowing visualization of the needle trajectory with respect to the organ models [17] (Figure 3a). In a similar percutaneous setup, interventional radiology (that is ablations of lesions in the kidney) indicated that electromagnetic-based navigation of ultrasound devices in preinterventionally acquired CT or MRI image planes improves the accuracy of needle placement [19–21]. Hence, the future use of US navigation could also help to further refine the needle-tracking technology.

Despite the potential advantages of electromagnetic tracking, fluoroscopy and (cone-beam) CT devices were shown to reduce the electromagnetic-tracking accuracy [22,23]. Research in to minimization and calibration efforts has partially overcome this electromagnetic-tracking inaccuracy in static environments [22]. Unfortunately, such technologies do not (yet) apply for dynamic surgical environments [e.g. moving (robot-assisted) surgical tools] [1].

Navigation during nephrectomy

During (robot-assisted) laparoscopic partial nephrectomy [(RA)LPN], various forms of CAS have been applied. Furukawa et al. [13] used a CT-based three-dimensional virtual reality roadmap of the kidney, tumor, and vasculature that facilitates selective arterial clamping presented in the surgeon's console parallel to the laparoscopic feed using the TilePro function (Figure 2b). A comparison of this approach with traditional clamping procedures not only indicated virtual reality assistance was feasible, it was also shown to reduce the decrease in estimated glomerular filtration rates early after surgery [24]. Here, the use of an iPad can help facilitate the interaction with the virtual reality model, thereby improving the intraoperative appreciation of the hilar vascular anatomy [25]. Alternatively, Wang et al. [26] describe the use of a manually positioned two-dimensional augmented reality overlay, presenting a CT-model in the laparoscopic feed (i.e. static screenshots). Comparisons between patients receiving augmented reality guidance and those that went without, suggested the technology could help reduce the operating time and reduce blood loss values. For open liver surgery, similar manual two-dimensional augmented reality overlays have been helpful in localizing multiple tumor lesions within the organ [27]. Ukimura and Gill [21] used a near-infrared (NIR) optical tracking system (OTS) to support the automatic alignment of such augmented reality CT models in the two-dimensional laparoscopic feed, during (non-robotic) LPN. Although they indicate the navigation accuracy was sufficient for determination of the resection line, the need for a technology able to correct for tissue deformations was also mentioned.

For intra-abdominal vision-based tracking, colored and radiopaque needle-shaped fiducials were fixed in the kidney surface as to support the alignment of the cone-beam CT models with the two-dimensional real-time laparoscopic and two-dimensional fluoroscopy feed (Figure 2c) [14]. Though the navigated setup was successful, the increased X-ray dose was considered to be a limitation for wider implementation. Whereas the use of intra-abdominally placed fiducials did seem to support image registration, others have reported some limitations related to such an approach: fiducials could potentially physically hinder the tumor resection; visualization of the fiducials in the surgical environment could be challenging; and both placement (before navigation) and removal (after navigation) adds to the invasiveness of the procedure [1]. As alternative, metabolizable fiducials (CT-opaque and fluorescent) have been suggested (Figure 2d) [15]. Extension with fluorescence, however, does rely on the surgical procedures to be performed with a laparoscope capable of fluorescence imaging.

To increase the acceptance of US guidance during RALPN, an innovative DROP-IN US probe was designed [28,29] (Figure 4). This DROP-IN probe can be

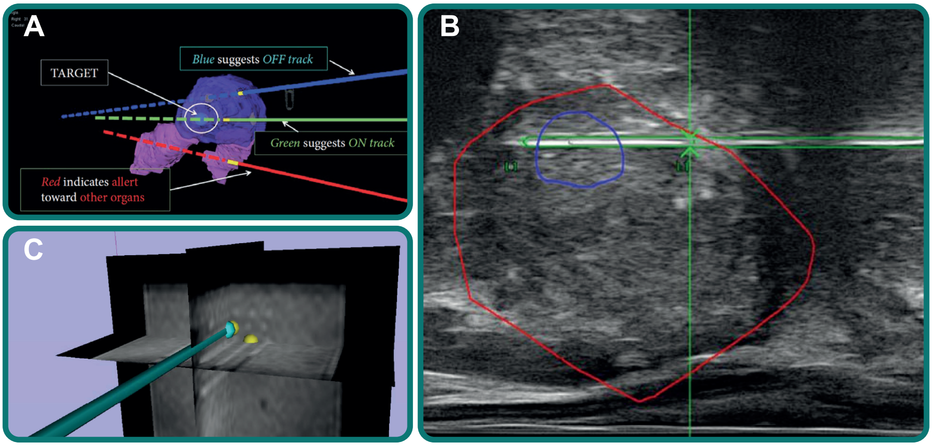

Figure 3. VR and AR technologies for needle-navigation to prostate lesions. (a) *CT-based VR model of the prostate displaying current needle track with respect to different organ models [17].* ***(b)*** *MRI-based navigation for targeted biopsy of the prostate displayed over the real-time TRUS images [12].* ***(c)*** *MRI-only-guided VR navigation for targeted biopsy in a phantom study [18].*

positioned with superior degrees of freedom, using laparoscopic tools. Via laparoscopic vision-based tracking of a chequered-pattern fiducial on the DROP-IN US (comparable to those used for crash test dummies), the two-dimensional US images could be directly projected as augmented reality overlay in the laparoscopic feed (Figure 4a). Combined with tracking of the robotic arms, this helped realize a three-dimensional navigation in a phantom setup (Figure 4b-c) [30,31].

REPRODUCTIVE ORGANS

For the reproductive organs, navigation efforts have been reported for the primary tumor and lymphatic involvement. In this application, next to ultrasound and MRI, also single-photon emission computed tomography (SPECT/CT), radiotracing, and fluorescence imaging have been used during the guidance process.

Navigation towards the primary tumor lesions

Transrectal US (TRUS)-guided biopsy in prostate cancer is commonly performed based on the lesion location defined by preoperative MRI images [32]. Recently, next to research systems, three-dimensional MRI-based navigation of TRUS has become commercially available (Figure 3) [33]. For registration, electromagnetic tracking, mechanical tracking, and image-based registrations have been used [33]. To enhance the insight into the relevant anatomy (e.g. prostate–bladder interface, seminal vesicles, distal prostate boundary, lesion location, biopsy tracks, neurovascular bundles, and urethra), TRUS-based navigation has also been applied in robot-assisted laparoscopic prostatectomy (RALP). Using US vision-based registration in combination with mechanical tracking, the two-dimensional TRUS

Figure 4. DROP-IN US technology. (a) *In-vivo application during (RA)LPN [28]. An AR overlay is shown directly in the laparoscopic-feed, displaying the real-time ultrasound imaging within the anatomical context.* ***(b)*** *Tracked DROP-IN ultrasound was used to generate a 3D model of the tumor* ***(c)*** *for navigation in a phantom (RA)LPN setup [30].*

automatically followed the position of the robotic tools, displaying the relevant US plane in the surgical console using the TilePro function [34]. Similar to such an automatic TRUS setup, robotic US acquisition has shown promising results for reproductive assistance and guidance for interventions in the abdomen [35]. The intraoperative use of three-dimensional virtual reality displays (based on preoperative TRUS and MRI) parallel to the laparoscopic-feed during RALP was said to further refine the resection accuracy in the vicinity of the cancer lesion, yielding 90% negative surgical margins [36] (Figure 5a). Such virtual reality models have also been suggested to facilitate nerve-sparing during pelvic surgery [38]. To enhance the urologist's preoperative appreciation of the patient anatomy (i.e. 'virtual therapy concept'), the virtual reality models were also three-dimensionally printed [39]. To further increase the information integration, for example, the neurovascular bundle and the biopsy proven cancer region, the use of direct augmented reality overlays in the two-dimensional laparoscopic feed have been studied (Figure 5b-c) [21,37]. The first study used a NIR OTS for the registration, thereby supporting the identification of an appropriate resection line. The second study used vision-based tracking of fiducial pins (colored and echogenic) placed in the prostate surface to realize the augmented reality alignment. In the latter setup, to prevent tumor spillage, the fiducial pins had to be removed together with the prostate itself. Unfortunately, both setups suffered from surgery-induced tissue deformations [21,37]. Lanchon et al. used transurethral US (TUUS) as alternative for TRUS [40]. In a phantom study using (US) vision-based tracking of fiducial pins, augmented reality models, formed using motorized TUUS, were displayed on the two-dimensional laparoscopic feed. Alternatively, the above mentioned DROP-IN US probe technology may in the future also support US navigation during prostatectomy [28,29]. In indications, where electromagnetic tracking is feasible, perhaps also commercially available US-navigation setups, as applied in interventional radiology, may find their way into prostate cancer surgery [19].

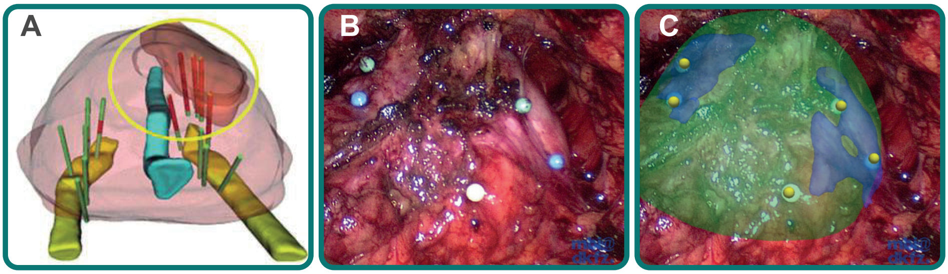

Figure 5. VR and AR technologies during prostatectomy. (a) *A TRUS/MRI-based VR model to be used in parallel to the laparoscopic view [36]. Different structures are shown: prostate (pink), ureter (blue), neurovascular bundles (yellow), biopsy-proven tumor lesion (red), and tumor biopsy cores (green (tumor negative) and red (tumor positive) cylinders).* ***(b)*** *After placement of intraabdominal fiducials (colored and echogenic pins in the prostate surface),* ***(c)*** *TRUS-based AR overlay of the prostate (green) and neurovascular bundles (blue) could be shown during (RA)LP [37].*

Navigation for the management of lymphatic disease

Navigated approaches have successfully been used to identify lymph nodes suspected to harbor metastases. Uniquely, in these procedures, nuclear molecular imaging approaches, namely preoperative SPECT/CT and intraoperatively acquired freehand (fh)SPECT [41], have provided the roadmaps for navigation.

The PSMA-specific tracer ^{111}In-PSMA-I&T has supported the radio-guided resection of metastasis-harboring lymph nodes during open salvage procedures [42]. Preoperative PET/CT or PET/MRI using ^{68}Ga-PSMA-HBED-CC supported patient selection and procedural planning. Intraopertively, fhSPECT was successfully applied to display the lesion location in two-dimensional augmented reality and support three-dimensional virtual reality navigation of a gamma probe (NIR OTS tracking) [42] (Figure 6). The acoustic readout of the gamma probe supported compensation of navigation inaccuracies when present. A similar navigation approach, using SPECT/CT, was used to identify (sentinel) lymph nodes that accumulated indocyanine green (ICG)-^{99m}Tc-nanocolloid [44]. In addition to acoustic gamma-tracing, non-integrated NIR fluorescence imaging was used as confirmatory modality. To integrate fluorescence imaging in the navigation workflow, SPECT/CT- or fhSPECT-based navigation of the fluorescence camera itself was applied in both prostate and penile cancer patients [43,45,46]. In these studies, an augmented-reality-SPECT(/CT) overlay was presented in the two-dimensional fluorescence camera feed and supported the detection of the injection site (primary tumor) and sentinel lymph nodes (Figure 6). Fluorescence imaging allowed for high-resolution real-time correction of deformation-induced navigation inaccuracies. Phantom studies indicated this same navigated fluorescence camera concept could become an integral part of robot-assisted procedures [47].

In an attempt to improve the radio-guidance during laparoscopic interventions, a DROP-IN gamma probe was developed, and evaluated during early robot-assisted porcine surgery and on ex-vivo clinical specimens [48] (Figure 7a). To connect this technology to the CAS concept, in a phantom setup, a combination of chequered pattern vision-based, NIR OTS, and mechanical tracking, supported the generation of DROP-IN fhSPECT-images and the according navigation approaches (Figure 7b) [49].

DISCUSSION

During the past decade, a lot of exciting and promising CAS developments have opened the way for navigation setups to be used in urology.

Registration of (preoperative) imaging datasets with the surgical view helps to generate virtual reality and augmented reality environments that support the navigation process in two- or three-dimensions. The greatest limitation for these navigation setups so far is the registration accuracy and resulting navigation precision. This is also the area where further technical improvements are urgently needed. A consequence of the current inaccuracies is the requirement that virtual reality and augmented reality navigation approaches have to be benchmarked against the real-world surgical environment. This is especially critical when the surgical procedures are performed in soft-tissue structures that suffer from surgically induced deformations. In that sense, navigation procedures do not replace the surgeon's expertise, but rather improve the procedural accuracy and efficiency by increasing both insight in the anatomy/disease and the focus on the anatomies critical for surgery. In the end, the urologist is still required to make his/her expert call on the execution of the procedure. The quality of the virtual reality and augmented reality displays, however, can greatly influence the value of navigation approaches. Therefore, improved visualization methods that determine which virtual data are displayed during different phases of the surgical procedure (i.e. relevance-based virtual reality/augmented reality) [50], or visualization methods that facilitate improved augmented reality integration into the real-world surgical view (e.g. three-dimensional depth perception) [1] should be considered.

To link the navigation process to the real-world surgical environment, some form of real-time imaging feedback is instrumental. When the targets cannot be defined by eye, dedicated intraoperative imaging modalities provide outcome, for example, fluoroscopy, US, gamma tracing/imaging, or fluorescence imaging. The modality of choice, then, is predominantly defined by the characteristics of the target and the modality's neutrality with regard to enhanced patient burden. This means that invasive approaches, for example, X-ray modalities or the requirement of placing invasive fiducial markers, should ideally be replaced by the non-invasive alternatives that have become available during recent years.

The intraoperative imaging modality should also be able to accurately track the visualization of the targeted tissue with respect to a navigation reference

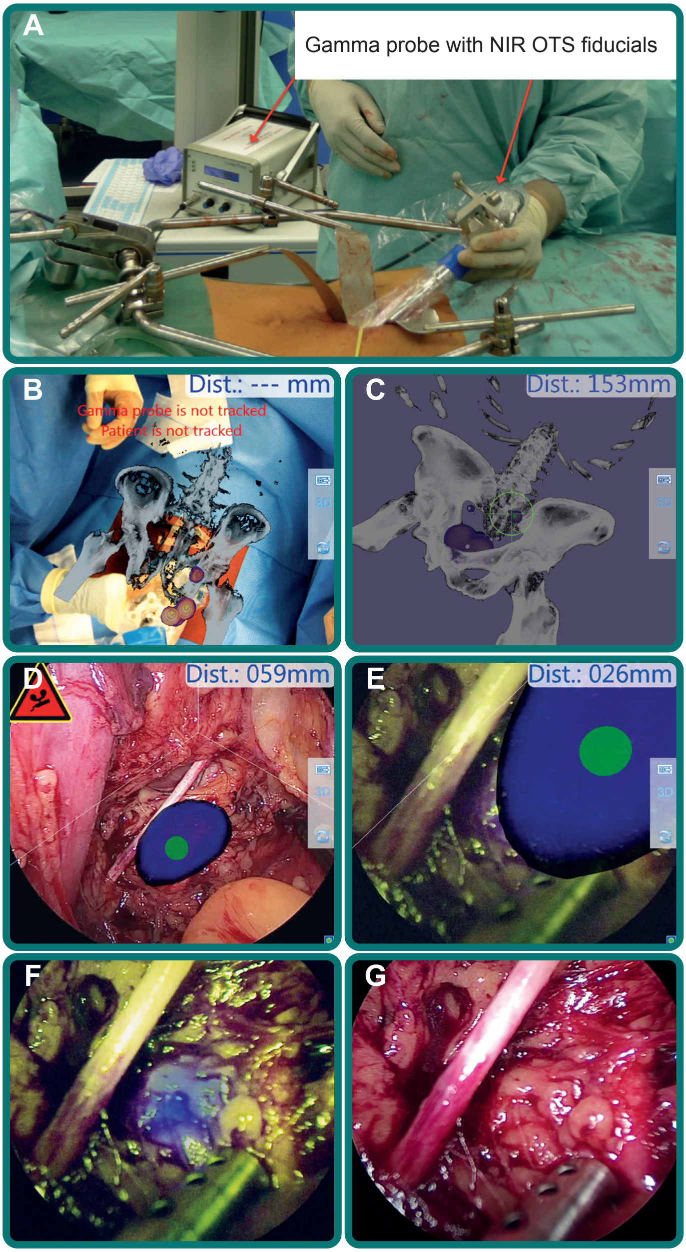

Figure 6. VR and AR technologies for navigation in the management of lymphatic disease. (a) *Intraoperative setup of navigated gamma probe (using NIR OTS tracking) towards metastatic LNs during open salvage prostatectomy (navigation based on fhSPECT) [42].* ***(b)*** *SPECT/CT-based navigation of a fluorescence camera towards sentinel LNs in penile cancer. AR SPECT/CT overlay was shown in the 2D camera-feed.* ***(c)*** *3D VR navigation of a gamma probe towards sentinel LNs in prostate cancer.* ***(d)*** *fhSPECT-based navigation of a fluorescence laparoscope towards sentinel LNs in prostate cancer, using an AR overlay directly shown in the 2D laparoscopic-feed [43].* ***(e)*** *AR overlays guided the fluorescence laparoscope to the vicinity of the LN.* ***(f)*** *Fluorescence imaging (fluorescence is shown in blue) confirmed the precise target location* ***(g)*** *not clearly visible by eye.*

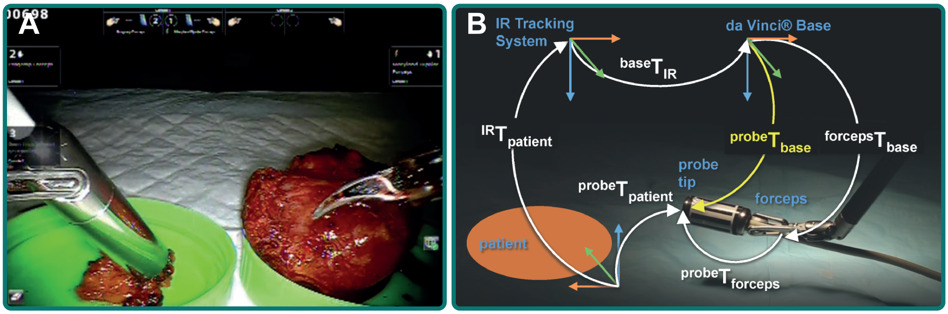

Figure 7. DROP-IN gamma probe technology. (a) *Ex-vivo application of the DROP-IN gamma probe, scanning LN package and prostate.* ***(b)*** *Tracked DROP-IN gamma probe (using a combination of tracking techniques) to create fhSPECT images for navigation purposes in a laparoscopic phantom LN setup [49].*

frame (i.e. the position of the target with respect to the navigated tools). Again, the indication and operating room setup define the most ideal tracking approach. That said, a combination of tracking techniques will most likely provide the highest accuracy [49,51]. For needle-based procedures, electromagnetic tracking and/or the more experimental fiber bragg grating tracking techniques will possibly work best [52]. Electromagnetic tracking, however, currently suffers from the use of metal equipment in the surgical environment. Hence, for surgical resections, a combination of NIR OTS, mechanical-tracking, and vision-based-tracking (e.g. using machine learning methods such as deep-learning) seems to hold most promise [53]. These preferences may, however, change when the individual technologies evolve.

CONCLUSION

Although there is still a lot of room for refinement, we believe the presented navigation efforts provide the first steps towards a promising future for computer-assisted urological surgery. This is strengthened by parallel developments in medical imaging devices, disease-specific tracers (e.g. ^{99m}Tc-PSMA-I&S) [42], and surgical tools. The up rise of robot-assisted procedures, thereby, provides a valuable platform for the integration of new modalities, for example, fluorescence imaging, DROP-IN modalities, and navigation setups.

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